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# A PROGRAM FOR COMPUTING TRANSMISSION OF PLANE ELECTROMAGNETIC WAVES THROUGH AN INHOMOGENEOUS PLASMA SLAB

Prepared by

D. C. Pridmore-Brown
Plasma Research Laboratory

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## FOREWORD

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Approved

R. X. Meyer

R. X. Meyer, Director
Plasma Research Laboratory

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

Gregory S. Mayforth

Gregory S. Mayforth
Lieutenant, United States Air Force
Project Officer

## ABSTRACT

A computer program for calculating plane wave transmission through an inhomogeneous cold plasma slab is described. The program accepts arbitrary profiles (including jumps) in number density and collision frequency. It prints out the electric and magnetic field profiles for the angles of incidence, direction of incidence, and polarizations of the wave that are called for. It also gives the reflection and transmission coefficients in each case.

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# I. INTRODUCTION

In estimating the attenuation and reflection of plane electromagnetic waves by a plasma layer it is often adequate to replace the layer by an equivalent one with uniform properties, for which the transmission loss is given by a simple formula (Ref. 1). On the other hand, in cases where the plasma properties vary significantly in the space of a wavelength, the uniform slab approximation is not justified. Furthermore, in studying breakdown under intense electromagnetic fields one is interested in the electric field profile in the vicinity of points where the dielectric constant goes to zero, and then it is clearly necessary to take account of the variation in the dielectric constant. Finally it is useful to have a systematic way for comparing existing programs (Refs. 2 through 4) and for checking estimates based on equivalent homogeneous slabs against exact calculations.

For these reasons it was decided to write a computer program for the inhomogeneous case that would be as flexible and easy to use as possible. The present report describes the program and gives a listing of it in the hope that it may also be of value to others.

The program applies to a cold plasma that is characterized by its electron number density and electron -neutral collision frequency profiles. It is designed to be as flexible as possible in the following respects. The user is free to input any arbitrary profiles of number density and collision frequency (including discontinuities) by listing the values of these quantities over any arbitrary set of corresponding abscissa values. He can call for the calculations to be performed for any number of frequencies and for any uniformly spaced sequence of angles of incidence, and for either or both polarizations of the incident wave. Finally he can have the wave be incident on the slab from either side. The computer output lists the collision frequency and number density profiles that were input. It then tabulates the transverse electric and magnetic field profiles, the dielectric constant profile, and the profile of the absolute value of the total electric field through the slab for

each case (angle of incidence, frequency, and polarization) that was called for. Finally it gives the reflection and transmission coefficients.

The next section shows some of the details of the formulation. The following one gives the exact format in which the data must be input and shows a sample of the output in an illustrative case. Finally the program itself is listed in the Appendix.

## II. FORMULATION

The plasma slab is considered to be contained in the region $0 \le x \le d$ with the xy plane being the plane of incidence. For a plane wave incident on the slab at an angle $\theta$ with respect to the x-axis, Maxwell's equations take the form

$$\frac{\partial E_z}{\partial x} = -i\omega B_y$$

$$-i\omega \frac{\partial B_y}{\partial x} = k_0^2 (\beta^2 - K)E_z$$

$$B_x = (\beta/c)E_z$$

for the TE mode (for which $E_x$, $E_y$, and $B_z$ are zero) and

$$\frac{\partial B_z}{\partial x} = \frac{i\omega}{c^2} K E_y$$

$$\frac{i\omega}{c^2} K \frac{\partial E_y}{\partial x} = k_0^2 (\beta^2 - K)B_z$$

$$E_x = -(\beta c/K)B_z$$

for the TM mode (for which $B_x$, $B_y$, and $E_z$ are zero). Here $\beta = \sin\theta$ and $k_0 = \omega/c$, where $\omega/2\pi$ is the frequency. The dielectric constant K for a cold plasma is given by

$$K = 1 - \frac{\omega_p^2}{\omega(\omega + i\nu_c)}$$

where $\nu_c$ is the electron-neutral collision frequency and where $\omega_p^2$, the square of the plasma frequency, is proportional to the electron number density n. If n is measured in electrons/$cm^3$ then

$$\omega_p^2 = 3.186 \times 10^9 n$$

For the TE mode the computer gives the profiles of $E_z$, $B_y$, and $|E_z|$. For the TM mode it gives the profiles of $E_y$, $B_z$, and $\sqrt{|E|_x^2 + |E|_y^2}$. The electric field components $E_z$ or $E_y$ are always normalized to unity on the incident side. The K profile is given in both cases.

Outside the plasma slab the waves are taken to be of the form

$$(1-R)\ E = \exp(ik_0\cos\theta\, x) - R\exp(-ik_0\cos\theta\, x) \qquad \text{for } x \le 0$$

$$(1-R)\ E = T\exp(ik_0\cos\theta\, x) \qquad \text{for } x \ge d$$

where E is any component of the electric field. Solving for R and T we find

$$R = \frac{E_1' - ik_0\cos\theta\ E_1}{E_1' + ik_0\cos\theta\ E_1}$$

$$T = (1-R)(E_2/E_1)\exp(-ik_0\cos\theta\ d)$$

in terms of $E_1$ and $E_2$, which are the values of E at x = 0 and x = d, respectively. (The prime denotes the x derivative.) The computer furnishes these values together with their decibel equivalents (defined as $20\log_{10}|R|$ and $20\log_{10}|T|$, respectively).

## III. DATA INPUT

The data are input on regular 80-column Fortran cards. At least 7 cards are required for each case. A particular case consists of a plasma slab defined by its thickness and its profiles of number density and collision frequency together with a set of plane waves having 1 to 10 different frequencies and any number of angles of incidence. Any number of cases can be run by stacking the corresponding groups of cards. The cards required to represent one case are as follows:

CARD 1 contains 6 two-digit numbers placed in first 12 columns as follows: (A one-digit number is preceded by 0, e.g., 3 becomes 03.)

| | |
|---|---|
| <u>Columns 1, 2:</u> | Number of stations at which number density is given. (See CARD 2.) Maximum allowed is 30. |
| <u>Columns 3, 4:</u> | Number of stations at which collision frequency is given. (See CARD 3.) Maximum allowed is 30. |
| <u>Columns 5, 6:</u> | Number of frequencies. Maximum allowed is 10. |
| <u>Columns 7, 8:</u> | Number of angles of incidence. (See CARD 6.) |
| <u>Columns 9, 10:</u> | Mode: 01 for TE, 02 for TM and 00 (or blank) for both. (Only one mode is computed at normal incidence.) |
| <u>Columns 11, 12:</u> | Direction of x-component of incident wave: 00 (or blank) if to the right (i.e., the direction in which the data on CARDS 2 - 5 is entered), 01 if to the left. |

CARD 2 lists stations (values of x/d) at which number densities are to be given. These values must be listed in increasing order starting with 0. (representing the front of the slab) and ending with 1. (representing the back). Each one

(including the last) requires a decimal point and occupies 5 columns, so the total number of columns is 5 times the first number entered on CARD 1. If more than 80 columns are required, two cards must be used, and the second then counts as the continuation of CARD 2. If at any station two values of the number density are to be given (corresponding to a discontinuity in the profile) then the corresponding station must appear twice. Thus a homogeneous slab requires 4 stations viz., 0., 0., 1., 1. .

CARD 3 lists stations at which collision frequencies are to be given. Remarks under CARD 2 apply.

CARD 4 lists number densities in multiples of $10^9/cm^3$ corresponding to the stations listed on CARD 2. The first and last values correspond to the media carrying the incident and transmitted waves respectively, and will normally be 0 (for vacuum). Each value occupies 5 columns, so the total number of columns used is the same as on CARD 2. The smallest possible number density is $10^5/cm^3$ (entered as .0001) and the largest is $10^{14}/cm^3$ (entered as 99999). Values between $10^{13}/cm^3$ and $10^{14}/cm^3$ are entered as 5 digit numbers without a decimal point.

CARD 5 lists collision frequencies in multiples of $10^9$ $sec^{-1}$ corresponding to the stations listed on CARD 3. Remarks under CARD 4 apply.

CARD 6 contains 3 numbers, each occupying 5 columns, including the decimal point.

Columns 1-5: Slab thickness in centimeters.

Columns 6-10: First angle of incidence to be run; 0 (or blank) corresponds to normal incidence. Thereafter this value is incremented by the number appearing in Columns 11-15 of this card until a total number of angles of incidence has been run equal to the number appearing in Columns 7, 8 of CARD 1.

Columns 11-15: Interval in degrees between successive angles of incidence.

CARD 7 lists wave frequencies in GHz. Each value occupies 5 columns, including the decimal point. The total number of frequencies listed must not be less than the number appearing in Columns 5 and 6 of CARD 1.

As a particular (rather artificial) example we consider a plasma slab 1.50 cm thick and having an electron number density which starts at $10^{12}/cm^3$ at $x/d = 0$, falls linearly to $10^{11}/cm^3$ at $x/d = .63$, at which point it jumps to $10^{11}/cm^3$, and then falls off linearly to zero at $x/d = 1$. We take the collision frequency to follow a triangular distribution, 0 at $x/d = 0, 1$ and $10^6\ sec^{-1}$ at $x/d = .5$. We call for one angle of incidence 37.5 deg, and one frequency, 3 GHz. We ask for the wave to be incident from the right and polarized in the TM mode. The input data as it would be entered on the seven cards is shown in Fig. 1. The corresponding output is shown in Fig. 2. The results (in this case the real and imaginary parts of $E_y$, $B_z$, and K, and the value of $\sqrt{|E_x|^2 + |E_y|^2}$) are printed out at intervals of $x/d = .1$ except at jumps where they are printed out twice, to the left and to the right of the jump. The electric field is always normalized to unity on the incident side. The fact that in the printout it is unity at $x/d = 1$ serves as a reminder that the wave was required to be incident on this side of the slab. On the transmitted side we have a single plane wave in free space for which $E_y/cB_z = -\cos(37.5^\circ)$.

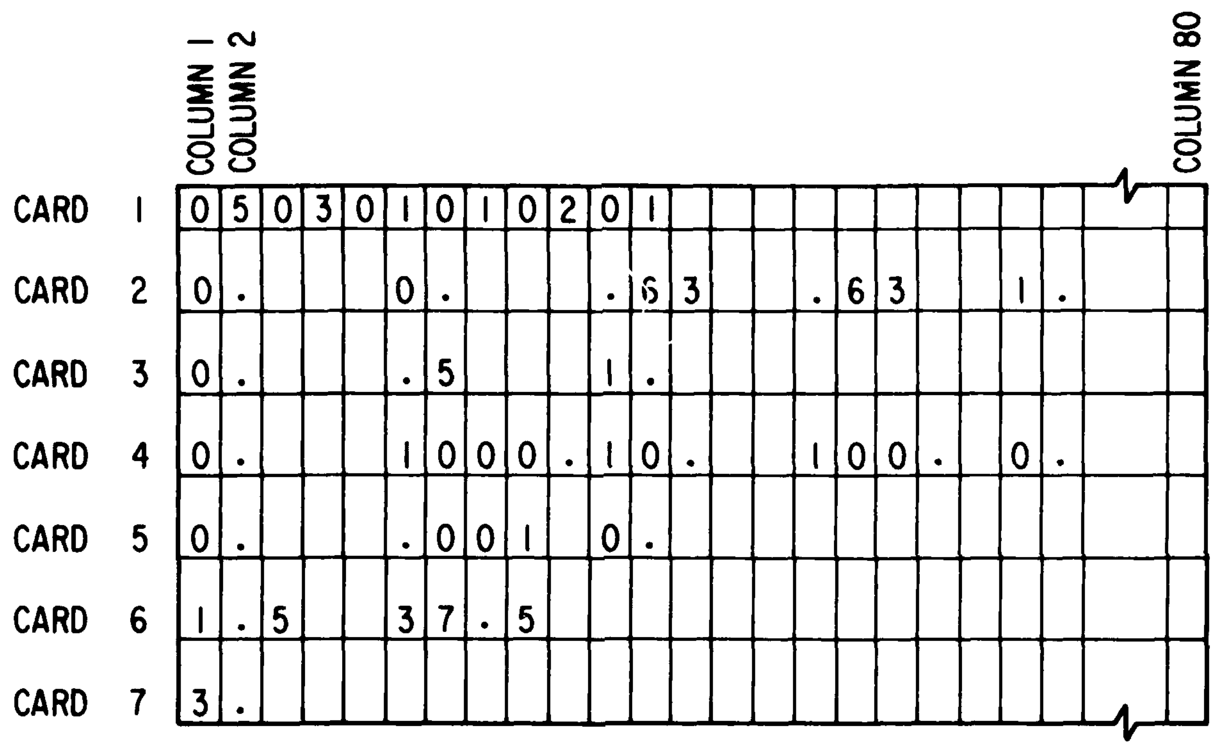


Figure 1. An Example of Input Data

TRANSMISSION THROUGH PLASMA SLAB

NUMBER DENSITY AND COLLISION FREQUENCY PROFILES (SLAB THICKNESS D = 1.500 CM)

| X/D | N | X/D | C |
|---|---|---|---|
| 0. | 0. | 0. | 0. |
| 0. | 1.00E+12 | .50 | 1.00E+06 |
| .63 | 1.00E+10 | 1.00 | 0. |
| .63 | 1.00E+11 | | |
| 1.00 | 0. | | |

TRANSVERSE MAGNETIC MODE (FREQUENCY = 3.00E+09 HZ, ANGLE OF INCIDENCE = 37.5 DEG)

| X/D | E | | B | | K | | ABS(E) |
|---|---|---|---|---|---|---|---|
| 0. | 3.8656E-01 | 1.8076E-01 | -1.6241E-09 | -7.9308E-10 | | | |
| 0. | 3.8656E-01 | 1.8076E-01 | -1.6241E-09 | -7.9308E-10 | 1.0000E+00 | 0. | .5422 |
| .10 | 4.2402E-01 | 1.4659E-01 | -1.2421E-09 | -1.7112E-09 | -7.9675E+00 | 0. | .4322 |
| .20 | 4.8824E-01 | 1.1314E-01 | -1.0031E-09 | -2.5437E-09 | -6.5583E+00 | 8.0196E-05 | .4525 |
| .30 | 5.7785E-01 | 8.4745E-02 | -8.6429E-10 | -3.2010E-09 | -5.1491E+00 | 1.3049E-04 | .5105 |
| .40 | 6.9225E-01 | 5.8529E-02 | -7.9510E-10 | -3.8812E-09 | -3.7400E+00 | 1.5080E-04 | .6071 |
| .50 | 8.3640E-01 | 3.1099E-02 | -7.7106E-10 | -4.2647E-09 | -2.3308E+00 | 1.4136E-04 | .7609 |
| .60 | 9.6646E-01 | 8.0530E-03 | -7.6907E-10 | -4.3223E-09 | -9.2161E-01 | 1.0194E-04 | 1.1992 |
| .63 | 9.8281E-01 | 5.1212E-03 | -7.6949E-10 | -4.2581E-09 | 4.8757E-01 | 2.1748E-05 | 1.9074 |
| .63 | 9.8281E-01 | 5.1212E-03 | -7.6949E-10 | -4.2581E-09 | 9.1033E-01 | 3.5205E-06 | 1.3113 |
| .70 | 8.8840E-01 | 2.2246E-02 | -7.7022E-10 | -4.2202E-09 | 1.0325E-01 | 3.5205E-05 | 7.7163 |
| .80 | 8.9157E-01 | 2.1052E-02 | -7.7308E-10 | -4.1108E-09 | 2.7291E-01 | 2.3144E-05 | 3.0052 |
| .90 | 9.3820E-01 | 1.2657E-02 | -7.7654E-10 | -3.9279E-09 | 5.1527E-01 | 1.0286E-05 | 1.7301 |
| 1.00 | 1.0000E+00 | 0. | -7.7826E-10 | -3.6602E-09 | 7.5764E-01 | 2.5716E-06 | 1.3461 |
| | | | | | 1.0000E+00 | 3.4615E-33 | 1.2112 |

REFLEXION COEFFICIENT = (-.0956, .8052) , -1.8 DB
TRANSMISSION COEFFICIENT = ( .4930, .3147) , -4.7 DB

Figure 2. An Example of Output Data

## REFERENCES


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3. E. Fletcher and F. A. Vicente, Exact Attenuation, Program FA-138-A, Applied Physics Dept., Electronics Division, Aerospace Corp.

4. P. E. Bisbing and M. McElvenny, Computer Solution for Plane Wave Propagation in One-Dimensional Plasmas (unpublished report), General Electric Co., Valley Forge, Pa. (1963).

# APPENDIX

# THE PROGRAM

```
              PROGRAM PLASMA(INPUT,OUTPUT,TAPE1=INPUT,TAPE2=OUTPUT)
000012        COMMON BETA,C(30),EPS,F(10),I,IMAX,INC,J,JMAX,KF,KO,M,N(30),XC(30)
             *,XN(30),Y(5),YP(5)
000012        DIMENSION E(40),MODE(2),S(3,40),TEMPS(50),X(40)
000012        COMPLEX EPS,PHASE,R,S,T
000012        REAL KO,KX,N
000012        DATA DX,DP,C1,C2,TPI/.01,.1,2.0944E-10,5.071E8,6.28319/
000012        DATA MODE/0550514050324221110355,0551501071605241110355/
000012        DATA EL,EU/4*5.E-6,4*5.E-4/,HMAX,HMIN/.010,.010/
000012        EXTERNAL DERIV
       *INPUT
000012      1 READ(1,200) IMAX,JMAX,NRF,NRA,M1,INC
000031        II = IMAX + 1
000033        READ(1,201) (XN(I),I=1,II)
000045        JJ = JMAX + 1
000047        READ(1,201) (XC(J),J=1,JJ)
000061        READ(1,202) (N(I),I=1,IMAX)
000073        READ(1,202) (C(J),J=1,JMAX)
000105        READ(1,201) D,THETA1,DTHETA
000116        READ(1,202) (F(K),K=1,NRF)
000130        WRITE(2,204) D,(XN(I),N(I),XC(I),C(I),I=1,JMAX)
000152        IF(JMAX.LT.IMAX) WRITE(2,205) (XN(I),N(I),I=JJ,IMAX)
000171        IF(INC.EQ.0) GO TO 300
       *INTEGRATION
000172      3 DO 150 KA = 1,NRA
000174        THETA = THETA1 + DTHETA*(KA-1)
000201        DO 150 KF = 1,NRF
000203        IF(M1.EQ.0.AND.THETA.NE.0.) SENSE LIGHT 1
000212        IF(M1.EQ.0) M = 1
000214        IF(M1.NE.0) M = M1
000216        GO TO 5
000217      4 M = 2
000220      5 RAD = THETA*.017453
000222        BETA = SIN(RAD)
000225        KO = C1*F(KF)*D
000230        KX = KO*COS(RAD)
000233        XP = 0.
```

```
000234          DO 6 K = 1,50
000235        6 TEMPS(K) = 0.
000240          Y(1) = 0.
000241          Y(2) = 1.
000242          Y(3) = 0.
000243          Y(4) = 0.
000244          Y(5) = -KX
000245          YP(1) = DX
000247          EPS = (1.,0.)
000251          I = 0
000252          J = 0
000253          L = 0
000254       10 I = I+1
000256          IF(XN(I).EQ.XN(I+1)) GO TO 160
000260          IF(I.GT.1)GO TO 80
000263       20 J = J+1
000265          IF(XC(J).EQ.XC(J+1)) GO TO 170
000267          IF(J.GT.1) GO TO 90
000272       30 L = L+1
000274          XP = XP+DP
000276          X(L) = Y(1)
000277          GO TO(40,45) M
000306       40 S(1,L) = CMPLX(Y(2),Y(3))
000317          S(2,L) = CMPLX(Y(4),Y(5))*(0.,1.E-8)/(3.*KO)
000336          GO TO 50
000337       45 S(1,L) = CMPLX(Y(4),Y(5))
000350          S(2,L) = CMPLX(Y(2),Y(3))*(0.,-1.E-8)*KO/3.
000366       50 S(3,L) = EPS
000373          IF(L.GT.1) GO TO 100
000377          CALL DERIV
000400       60 CALL F4AMRK(Y,YP,DERIV,4,0.,EU,EL,HMAX,HMIN,TEMPS)
000410       70 IF(Y(1) - (XN(I+1)-.2*DX)) 80,10,10
000415       80 IF(Y(1) - (XC(J+1)-.2*DX)) 90,20,20
000422       90 IF(Y(1) - (XP-.2*DX)) 60,30,30
000427      100 IF(Y(1) - (1.-.2*DX)) 60,110,110
        *OUTPUT
000434      110 PHASE = CMPLX(COS(KX),SIN(KX))
000443          R = (CMPLX(YP(2*M),YP(2*M+1)) + KX*(0.,1.)*S(1,L))/(CMPLX(YP(2*M),
         *YP(2*M+1)) - KX*(0.,1.)*S(1,L))
000511          T = (1.-R)*PHASE/S(1,L)*((0.,-1.)*KX*(M-1) + 2-M)
```

```
000547          DBR = 20*ALOG10(CABS(R))
000554          DBT = 20*ALOG10(CABS(T))
000562          S(1,L+1) = 1./S(1,L)
000575          DO 120 K=1,L
000576          S(1,K) = S(1,K)*S(1,L+1)
000610          S(2,K) = S(2,K)*S(1,L+1)*(1.-2.*INC)
000627          GO TO (115,116) M
000636      115 E(K) = CABS(S(1,K))
000644          GO TO 120
000645      116 E(K) = SQRT(REAL(9.E16*BETA*BETA*S(2,K)/S(3,K)*CONJG(S(2,K)/S(3,K)
               *) + S(1,K)*CONJG(S(1,K))))
000720      120 CONTINUE
000723          S(1,L) = (1.,0.)
000727          IF(INC) 135,130,135
000730      130 DO 131 K = 1,L
000732      131 X(K) = 1. - X(K)
000737          WRITE(2,206) MODE(M),F(KF),THETA,(X(L+1-J),(S(K,L+1-J),K=1,3),E(L+
               *1-J),J=1,L)
000773          GO TO 140
000774      135 WRITE(2,206) MODE(M),F(KF),THETA,(X(J),(S(K,J),K=1,3),E(J),J=1,L)
001027      140 WRITE(2,207) R,DBR,T,DBT
001042          IF(SENSE LIGHT 1) 4,150
001045      150 CONTINUE
001052          GO TO 1
         *JUMPS
001053      160 I = I+1
001055          IF(Y(1).GE.(XC(J+1)-.2*DX)) J = J+1
001064          IF(XC(J).EQ.XC(J+1)) J = J+1
001070          GO TO 180
001071      170 J = J+1
001073      180 DO 190 K = 1,2
001075          L = L+1
001077          IF(K.EQ.2) CALL DERIV
001102          X(L) = Y(1)
001104          GO TO (185,186) M
001113      185 S(1,L) = CMPLX(Y(2),Y(3))
001124          S(2,L) = CMPLX(Y(4),Y(5))*(0.,1.E-8)/(3.*KO)
001143          GO TO 190
001144      186 S(1,L) = CMPLX(Y(4),Y(5))
001155          S(2,L) = CMPLX(Y(2),Y(3))*(0.,1.E-8)*KO/3.
```

```
001173     190 S(3,L) = EPS
001202         TEMPS(4) = 0.
001203         IF(Y(1).GT.(XP-.2*DX)) XP = XP+DP
001211         GO TO 100
        *FORMATS
001212     200 FORMAT(7I2)
001212     201 FORMAT(16F5)
001212     202 FORMAT(16(-9PF5))
001212     204 FORMAT(1H1,30X,32HTRANSMISSION THROUGH PLASMA SLAB//68HONUMBER DEN
          *SITY AND COLLISION FREQUENCY PROFILES (SLAB THICKNESS D =F6.3,4H C
          *M)//21X,3HX/D,9X,1HN,13X,3HX/D,9X,1HC//(12X,2(F13.4,E13.3)))
001212     205 FORMAT(12X,F13.4,E13.3)
001212     206 FORMAT(11H0TRANSVERSE,A10,17HMODE (FREQUENCY =E10.3,25H HZ, ANGLE
          *OF INCIDENCE =F6.2,5H DEG)/5H0 X/D,16X,1HE,27X,1HB,27X,1HK,16X,6HA
          *BS(E)//(F5.2,3(E15.4,E13.4),F11.4)
001212     207 FORMAT(29H0REFLEXION COEFFICIENT     = (F6.4,1H,F6.4,3H) ,F6.1,3H D
          *B/29H TRANSMISSION COEFFICIENT = (F6.4,1H,F6.4,3H) ,F6.1,3H DB/)
        *INPUT REVERSAL
001212     300 II = (IMAX+1)/2
001216         DO 310 I = 1,II
001220         Z = XN(I)
001222         XN(I) = 1. - XN(IMAX-I+1)
001225         XN(IMAX-I+1) = 1. - Z
001230         Z = N(I)
001231         N(I) = N(IMAX-I+1)
001233     310 N(IMAX-I+1) = Z
001240         JJ = (JMAX+1)/2
001244         DO 320 J = 1,JJ
001245         Z = XC(J)
001247         XC(J) = 1. - XC(JMAX-J+1)
001252         XC(JMAX-J+1) = 1.-Z
001255         Z = C(J)
001256         C(J) = C(JMAX-J+1)
001260     320 C(JMAX-J+1) = Z
001265         GO TO 3
001265         END
```

```
              SUBROUTINE DERIV
002331        COMMON BETA,C(30),EPS,F(10),I,IMAX,INC,J,JMAX,KF,KO,M,N(30),XC(30)
             *,XN(30),Y(5),YP(5)
002331        COMPLEX EPS,V,W
002331        REAL KO,N,NX
002331        DATA C2,TPI/5.071E08,6.28319/

002331        NX = N(I) + (N(I+1)-N(I))*(Y(1)-XN(I))/(XN(I+1)-XN(I))
002343        CX = C(J) + (C(J+1)-C(J))*(Y(1)-XC(J))/(XC(J+1)-XC(J))
002355        EPS = 1. - C2*NX/(F(KF)*CMPLX(TPI*F(KF),CX))
002400        V = CMPLX(Y(4),Y(5))
002404        W = KO*KO*(BETA*BETA - EPS)*CMPLX(Y(2),Y(3))
002425        GO TO(2,1) M
002434      1 V = EPS*V
002442        W = W/EPS
002452        IF DIVIDE CHECK 10,2
002454      2 YP(2) = REAL(V)
002456        YP(3) = AIMAG(V)
002460        YP(4) =  REAL(W)
002461        YP(5) = AIMAG(W)
002463        RETURN
002463     10 Y(1) = 1.
002465        RETURN
002465        END
```

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Pridmore-Brown, David C.

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13 ABSTRACT

A computer program for calculating plane wave transmission through an inhomogeneous cold plasma slab is described. The program accepts arbitrary profiles (including jumps) in number density and collision frequency. It prints out the electric and magnetic field profiles for the angles of incidence, direction of incidence, and polarizations of the wave that are called for. It also gives the reflection and transmission coefficients in each case.

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